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THE LIGHT CUPVE OF TYPE I SUPERNOVAE

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ABSTRACT

Calculations of the intermediate and late time luminosity of type I supernovae based on 100% efficiency for optical emission of energy deposited by the Ni^{56} decay chain give good agreement with observations provided $M_{ej}\ v^{-2} = (2.2 \pm 0.5) \times 10^{17}\ M_{\odot}\ s^{2}\ cm^{-2}$ where M_{ej} is the ejected mass and v is the expansion velocity. Account must be taken of the escape of both gamma rays and positrons. These two escape processes as well as the early luminosity peak as calculated by Colgate and McKee are all consistent with the same value of M_{ej}/v^{2}.

INTRODUCTION

Type I supernovae are recognized by a characteristic light curve that has been outlined in several publications. Some of these use a superposition of many supernova light curves (Barbon et al 1973; Morrison and Sartori 1969). The problem with curves determined by superposition of many light curves is the variations that are produced by adjustment of explosion time and normalization of magnitude. It therefore seems preferable to compare a theory of supernova light curves with one or two careful and extensive measurements of individual light curves. Particularly, the older supernova NGC 4182 (Baade and Zwicky 1938; Van Hise 1974) and the more modern supernova NGC 5253 (Kirshner and Oke

1975) seem optimal because of the long period of observation (600 to 700 days) and the high peak luminosity. We will therefore consider these two as our standard.

NGC 4182 has been analyzed in terms of two exponential decays by Van Hise (1974). It was this analysis that caused many to seek an answer to the tantalizing suggestion that a factor of exactly 3/4 was involved in the transformation of the half-lives of a presumed $Ni^{56} \rightarrow Co^{56} \rightarrow Fe^{56}$ beta decay to the half-lives of the observed luminosity decay. It is the purpose of this paper to show that the apparent luminosity half-lives equal to 3/4 of the radioactive half-lives are an entirely fortuitous consequence of the progressive transparency of the expanding nebula.

We start with the work of Colgate and McKee (1969) who showed that the magnitude and width at half maximum of the early light curve of a type I supernova could be obtained by using the radioactive energy of 0.25 $M_\odot$ of Ni^{56} and accounting for diffusive escape of radiation. These calculations required the ejection of 0.75 $M_\odot$ of silicon burning products at a velocity of 1.5×10^9 cm s^{-1}. The maximum diffusive release of radiant energy occurs at an optical depth $\rho r/\lambda = \tau \simeq 3\ c/v$ where v is expansion velocity of the envelope. Approximately 1/2 the solar mass of matter was required to supply the total energy and opacity. Adiabatic expansion absorbs a fraction, 44%, of the radioactive energy before diffusive release at 6 days. The peak in the supernova light curve corresponds to 10^{43} ergs/s or a bolometric magnitude of 20 in the blue with no correction. These are the numbers one would obtain for the peak luminosity of type I supernova for a Hubble constant of 50. On the other hand, the larger Hubble constant of 100 currently being discussed would imply that the total luminosity would be closer to 4×10^{43} ergs/s and that 1 $M_\odot$ of Ni^{56} would have to be ejected. Furthermore, the transparency function that we are about to derive implies that the total kinetic energy of the ejected matter would have to be 2.7×10^{51} ergs and this would only make sense if one of the combination detonation models of an external helium envelope and an internal carbon-oxygen core suggested by Weaver and Woolsey (1980 were to be the cause of type I supernova.

DEPOSITION CALCULATIONS

The gamma-ray Monte Carlo photon transport code "MCP" (Cashwell et al 1973) of the Theoretical Design Division of Los Alamos was used to calculate the gamma ray deposition energy as a function of time for the gamma ray spectrum of the $Ni^{56} \rightarrow Co^{56} \rightarrow Fe^{56}$ decay scheme. The gamma ray absorption mean free path λ is adequately represented by a constant 35.5 g cm^{-2} for either the Ni^{56} or the Co^{56} decay spectrum. The detailed calculations confirm that the deposition function is determined by just ρr and is unaffected by the change in spectrum. The fractional deposition as a function of $\tau = \rho r/\lambda$ is given in Table I. An analytical fit is $D = G[1 + 2G(1 - G)(1 - .75G)]$ where $G = \tau/(1.6 + \tau)$.

Table I Deposition Function for a Uniform Sphere

$Ni^{56} \rightarrow Co^{56} \rightarrow Fe^{56}$ gamma rays.			
τ	D	τ	D
16	.965	1	.517
8	.930	½	.301
4	.857	¼	.158
2	.725	1/8	.080

For $\tau \leq \frac{1}{4}$, $D = 0.64\ \tau$; $\tau = \rho r/\lambda$.

Another model with the radioactive source restricted to the inner ¼ mass and 3/4 of the mass external as H and He gave the same deposition function within a few percent.

Figure 1 shows the product of the transparency function given in Table I and an exponential of half-life t_1. We characterize the transparency function by the time t_0, at which $D \simeq \frac{1}{2}$, i.e., when τ = 1. Figure 1 shows the product of the deposition fraction times the exponential for various ratios of t_0/t_1. The dashed line is drawn corresponding to an exponential of time constant 3/4 t_1, i.e., that modification of the exponential inferred from Van Hise's analysis of the early and late time light curves of type I supernovae. It is evident that at $t_0/t_1 = 4$, an approximate exponential with a half-life equal to 3/4 of t_1 results. In the model we are about to describe $t_0 = 20$ days for γ-ray transparency. The Ni^{56} half-life $t_1 =$ 6.1 days is roughly ¼ of t_0 (actually, $t_0/t_1 = 3.3$).

In a separate publication (Colgate, Petschek, and Kriese 1980) we give the justification for assuming that the energy deposition of electrons can be treated in the same fashion as the gamma rays but with a mean free path of $\lambda_\beta = 0.10$ g cm^{-2} rather than the gamma ray value of 35.5 g cm^{-2}. This also assumes that either no magnetic field is present or that the magnetic field is combed radially by the ejection of a relativistic mass fraction. The ejection of a relativistic mass fraction of a value necessary to comb a magnetic field radially is entirely consistent with our prior explanation of the relativistic shock ejection mechanism of cosmic ray formation. The energy in the magnetic field is of the order of 10^{39} ergs whereas that in the relativistic ejected mass fraction should be several 10^{49} ergs. In that case, t_0 for transparency to β-rays is about 370 days, about 4 (acutally 4.8) times the Co^{56} half-life of 77 days.

The implication is that the observed 4.8-day and 56-day half-lives are fortuitous combinations of a radioactive decay and a transparency function.

RESULTS

Thus, we recalculated the luminosity of type I supernova (Figs 2 and 3) by using (1) the diffusive release of Ni^{56} decay energy (Colgate and McKee 1969); (2) the progressive gamma ray transparency as calculated by the Monte Carlo gamma-ray simulation code and (3) the fractional deposition of positrons (Arnett 1979) using either zero magnetic field or a radially combed dipole field. After the initial black body peak, we assume 100% optical fluorescence efficiency from Fe^+ (Meyerott 1979). The deposition function determined by the Monte Carlo calculations is then applied to the beta energy source as well as the gamma source. When the nebula is one gamma-ray mean free path thick at $t_0 = 20$ days, good agreement with observations is obtained. The luminosity half-life of 56 days requires that M_{ej}

v_9^{-2} = 0.22 ± 0.05 where the ejected mass is in solar masses and v_9 is the expansion velocity in units of 10^9 cm s^{-1}.

KINETIC ENERGY OF EJECTED MATTER

The kinetic energy of the ejected matter (assuming a uniform density nebula) is $3/5\ M_{ej}\ v^2/2$. Using the estimate of M_{ej}/v^2 above this becomes $2.7 \times 10^{51}\ M_{ej}^2$ ergs where again M_{ej} is measured in solar mass units. When M_{ej} is 0.5 (v_9 = 1.5), the ejected kinetic energy is acceptable, 6.7×10^{50} ergs, but if a larger ejected mass is assumed, the energy requirements become severe. The conversion of 30% to 50% of the ejected fraction of a presupernova carbon core to Ni^{56} is possible in silicon burning (Truran et al 1967). Finally the temperature of the black-body phase of the light curve remains constant for the scaling $M_{ej}\ v_9^{-2}$ = constant.

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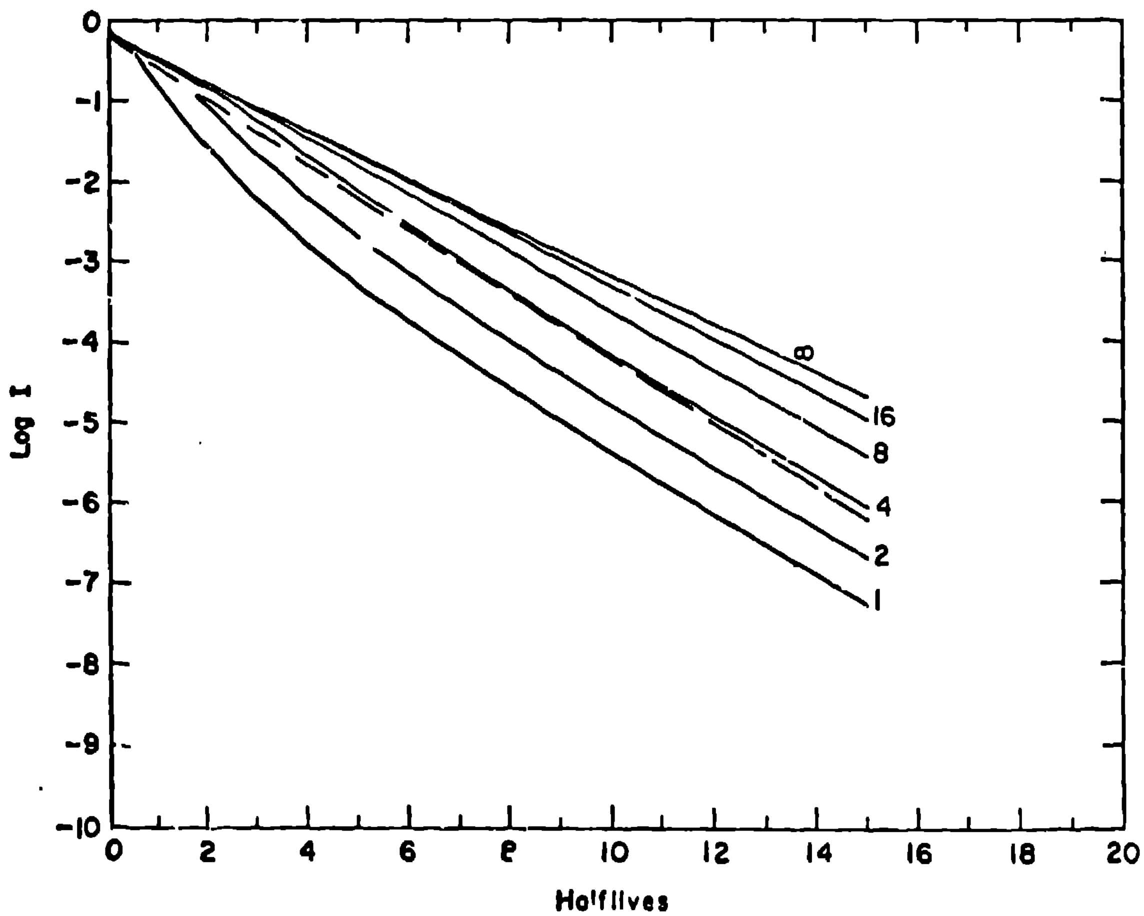

Fig. 1. We plot $D\,e^{-t\ln 2/t_1}$ for various values of t_0/t_1 where t_0 is the time at which deposition is ½. If we assume $d_{ej}/v^2 = \kappa$, then

$$\tau = \rho r/\lambda = \frac{\kappa}{\frac{4}{3}\pi t^2 \lambda} .$$ From Table I $\tau = 1$ when $t = t_0$ so that

$$t_0 = \left(\frac{\kappa}{\frac{4}{3}\pi \lambda} \right)^{\frac{1}{2}} .$$

The deposition D is a function of τ given in Table I. For our best fit model and the early decay of 6.1 days, $t_0/t_1 = 3.3$. In the second part of the decay where $t_1 = 77$ days, $t_0/t_1 = 4.8$.

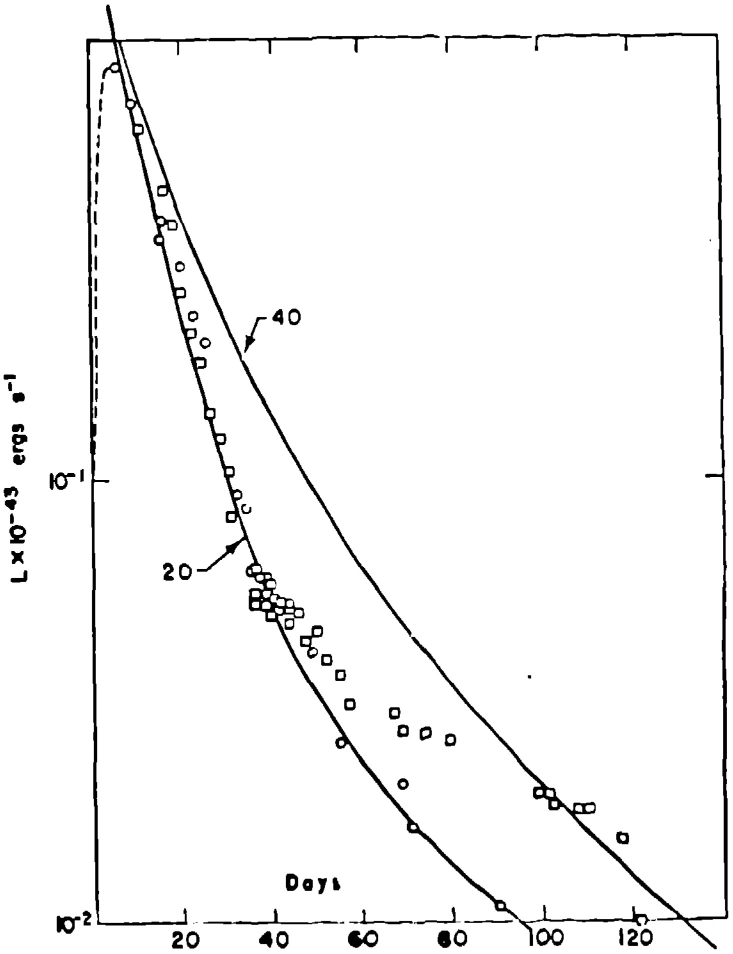

Fig. 2. The calculated luminosity at early and intermediate times for M_{Ni} = 0.25 solar masses and the corresponding deposition functions for τ = 1 at 20 days and 40 days. Gamma ray deposition and the Ni → Co → Fe decay determine the solid curves. The dashed curve is the modification of the deposition function due to diffusion and expansion (Colgate and McKee 1969). The extrapolation of the deposition curves reaches 2×10^{43} ergs s^{-1} at t = 0. The difference between this extrapolation and the dashed curve is due to heat energy converted to kinetic by expansion. The circles, give NGC 5253 data (Kirshner and Oke 1975) and the squares give NGC 4182 (Baade and Zwicky 1938; Van Hise 1974). The circles, NGC 5253, give a better fit. It may be that photometric corrections result in the disagreement of the squares in the interval 50 to 80 days.

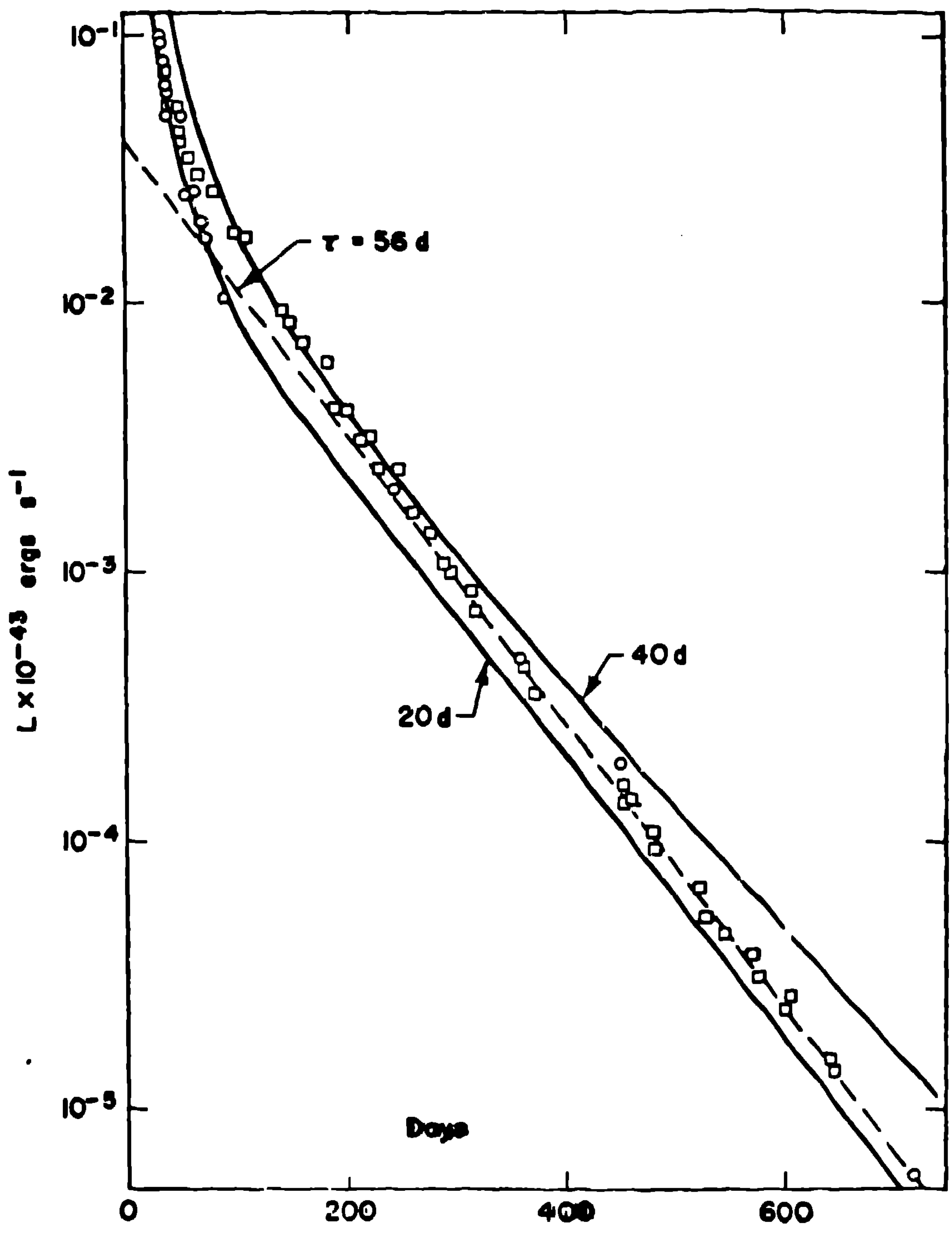

Fig. 3. Same as Fig. 2 for times out to 700 days. Here the curves are primarily determined by the deposition of positrons from the Co → Fe decay. The dashed line is a fit to the data with a slope corresponding to a 56-day half-life.